A novel phase in SU(3) gauge theory with many light fermions

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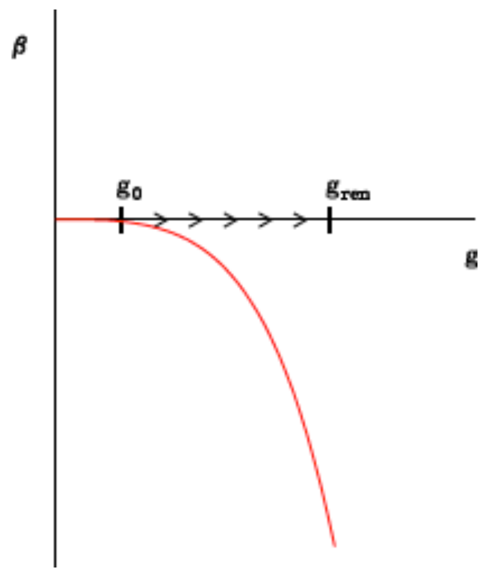
The many faces of gauge-fermion systems

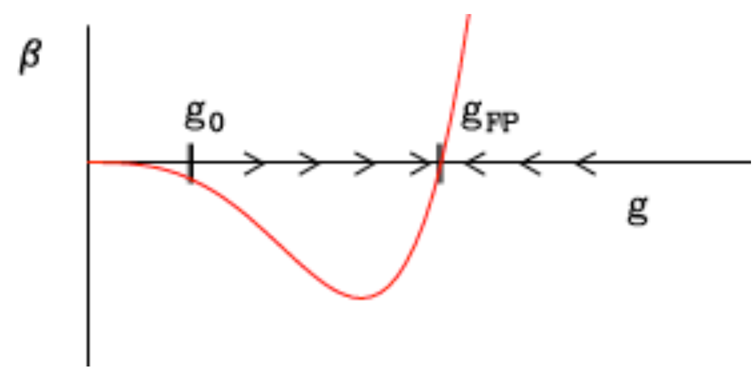
Renormalization group β function at 2 loops

$$\beta(g^2) = \frac{dg^2}{d\log(\mu^2)} = \frac{b_1}{16\pi^2} g^4 + \frac{b_2}{(16\pi^2)^2} g^6 + \ldots$$

$$b_1 = -11 + \frac{2}{3} N_f \,,$$
$$b_2 = -102 + \frac{38}{3} N_f$$



$N_f < 8.05$



$8 < N_f < 16.5$

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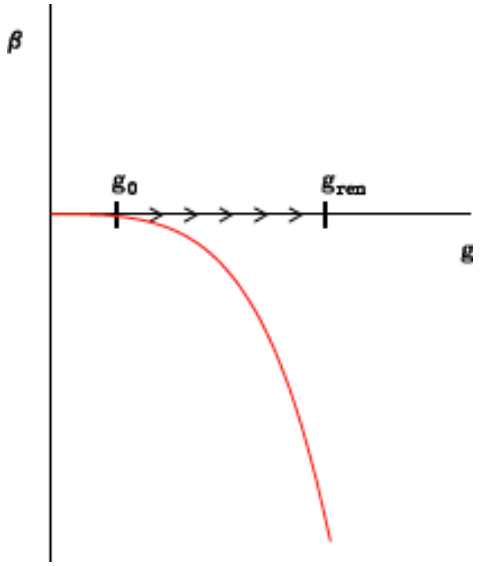

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Chirally broken & confining

- QCD with 2+1 (+1) flavors
- Original technicolor candidates

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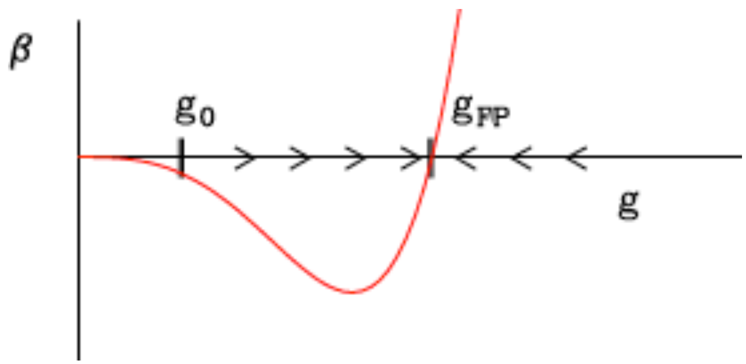
Conformal

- IRFP where g_0 is irrelevant
- universal anomalous dimension



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The many faces of gauge-fermion systems

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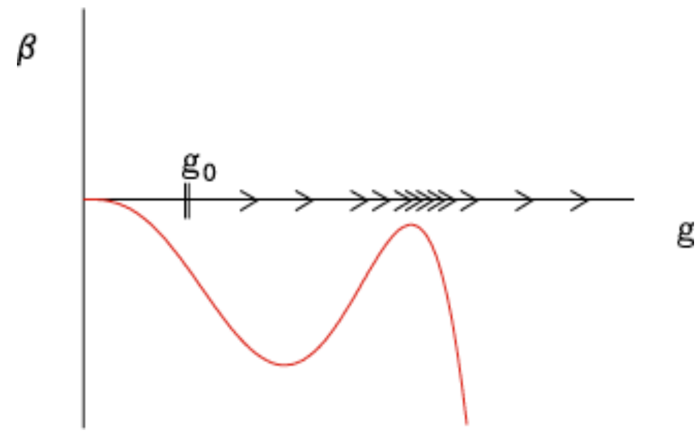
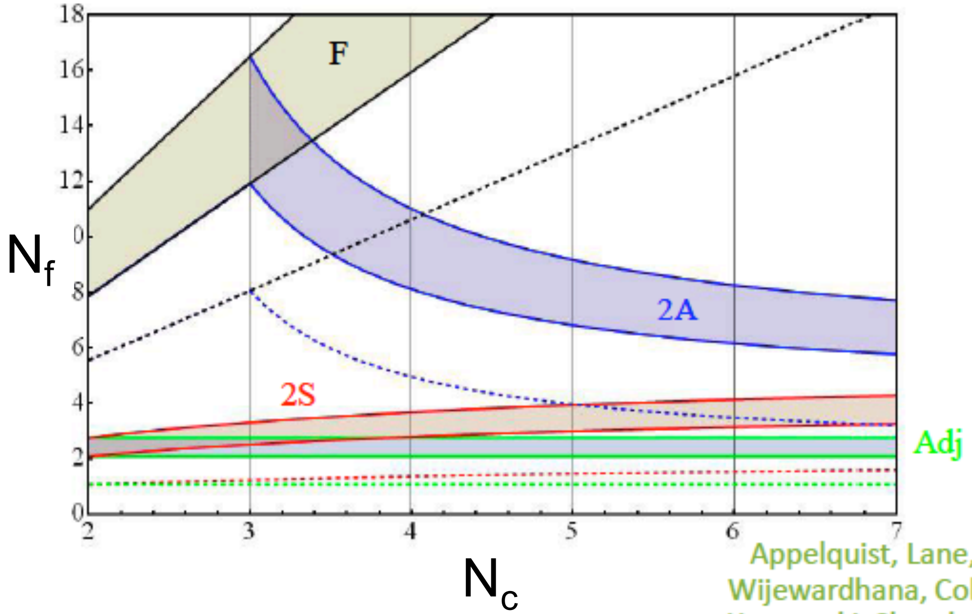
What we really want is walking



The gauge coupling changes slowly and the anomalous mass dimension remains large across an extended energy scale

Roadmap for the conformal window

S-D type calculations

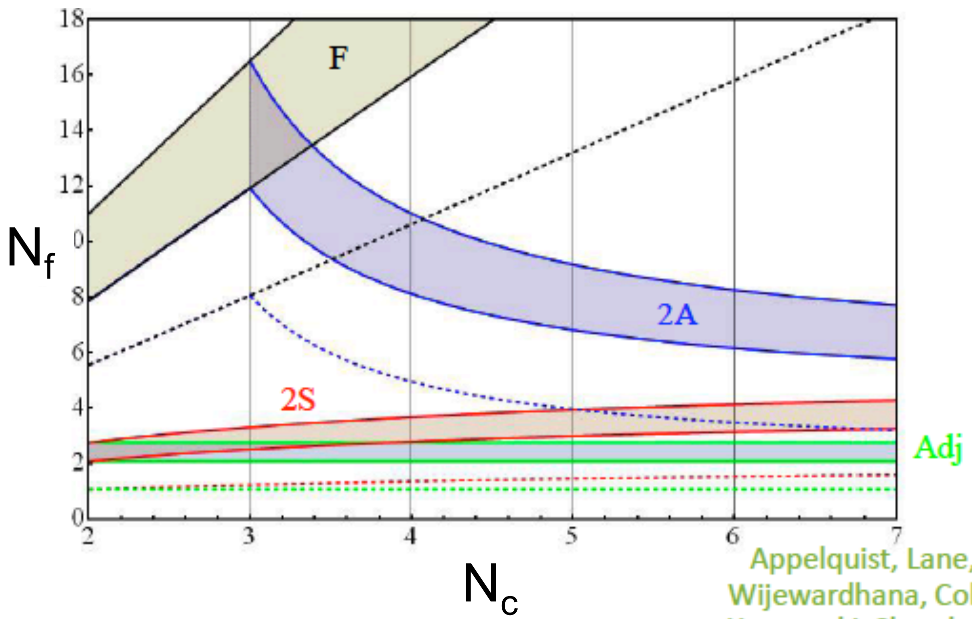


Appelquist, Lane, Mahanta, Wijewardhana, Cohen, Georgi, Yamawaki, Shrock, Dietrich, Sannino, Tuominen

- Which models are conformal?
- Which – if any - is walking?
- What is the anomalous mass ?
- S parameter?

Roadmap for the conformal window

S-D type calculations



Appelquist, Lane, Mahanta, Wijewardhana, Cohen, Georgi, Yamawaki, Shrock, Dietrich, Sannino, Tuominen

- What is the best approach to study these systems?
- Do we understand the systematics?

Don't be unpatient : QCD has a 25 year head start

A phase with novel symmetry breaking pattern

Strongly coupled systems can lead to unexpected phenomena:

N_f=12 and 8 flavors SU(3) with staggered fermions

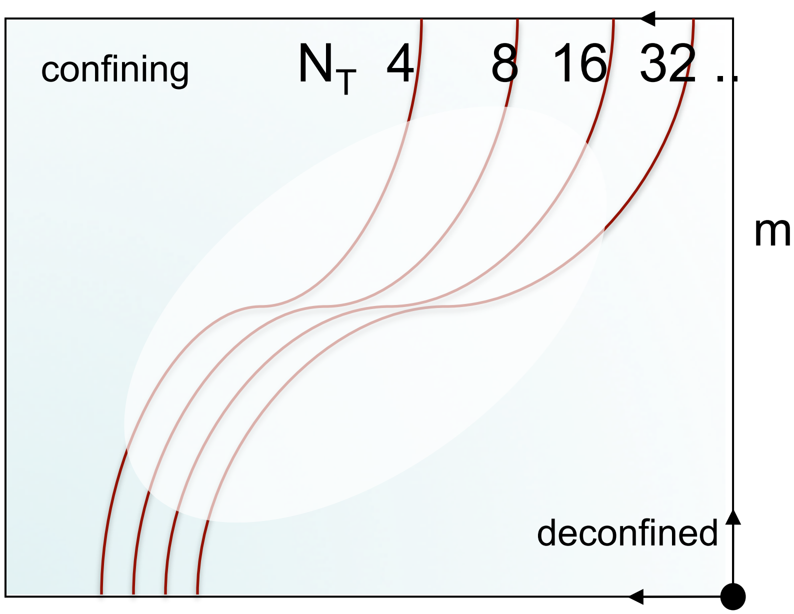
- 8 flavors: most likely chirally broken
- 12 flavors: still controversial

Goal: study the phase diagram both at zero and at finite temperature
and contrast the two systems

(Lattice action: it's a good one)

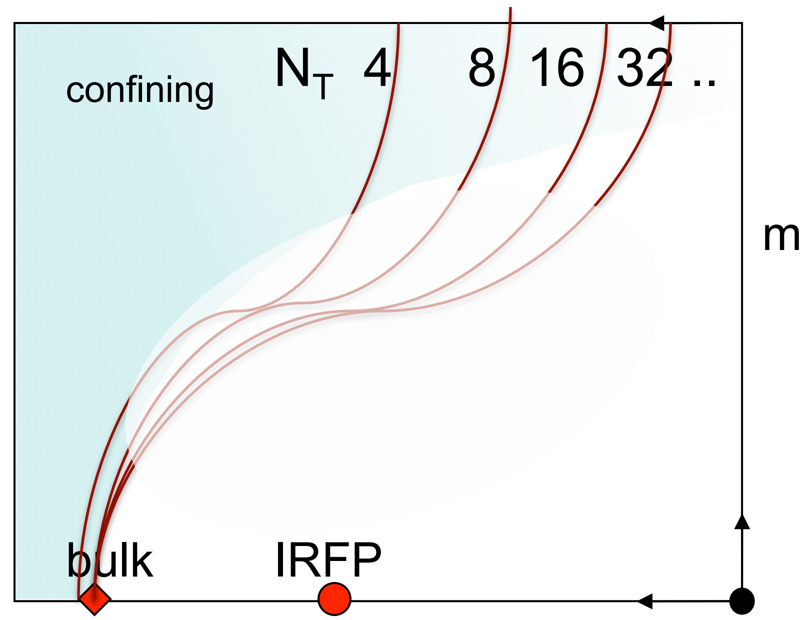
Why Finite temperature ?

QCD like



$\beta_c \rightarrow \infty$ as $N_T \rightarrow \infty$

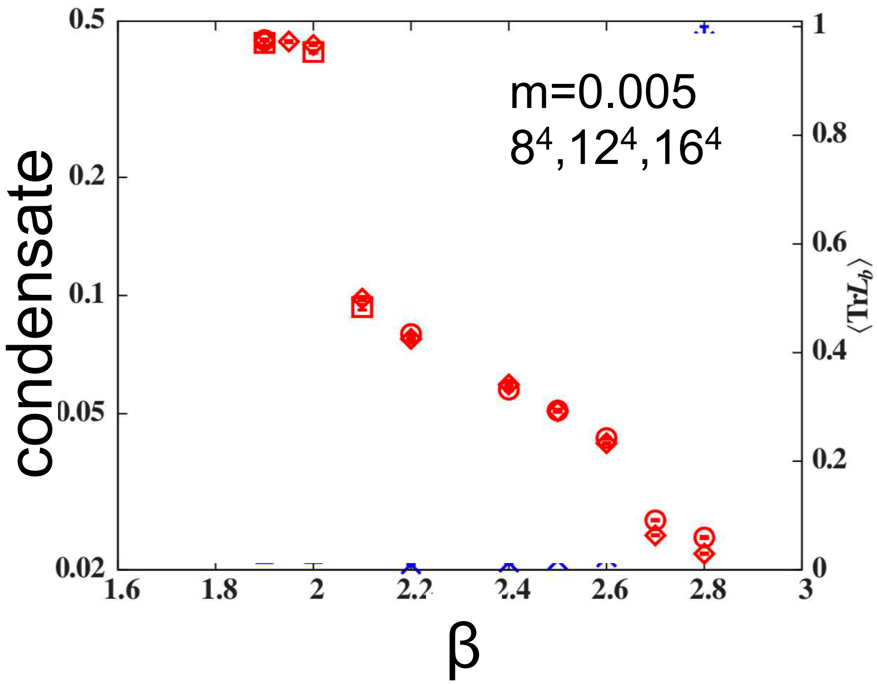
Conformal

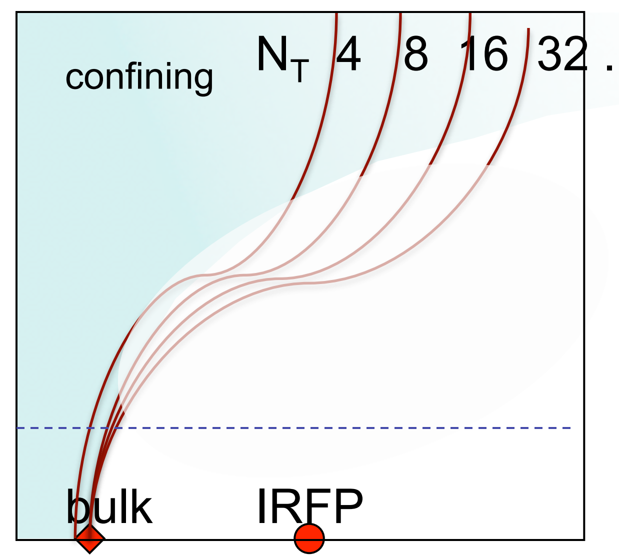


$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

The scaling of β_c is a good test of conformality (possibly)

The phase stucture of N_f=12





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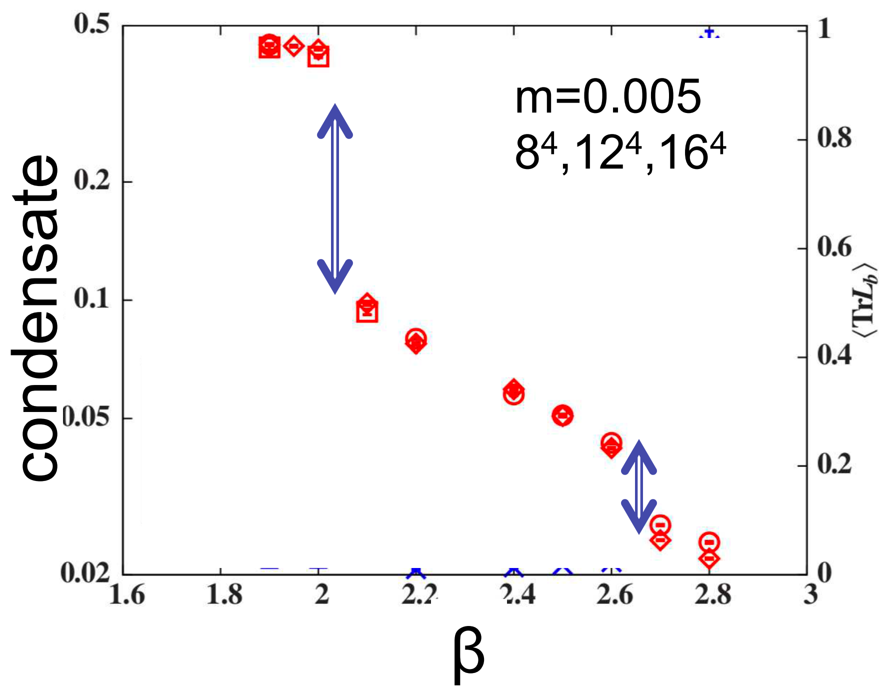
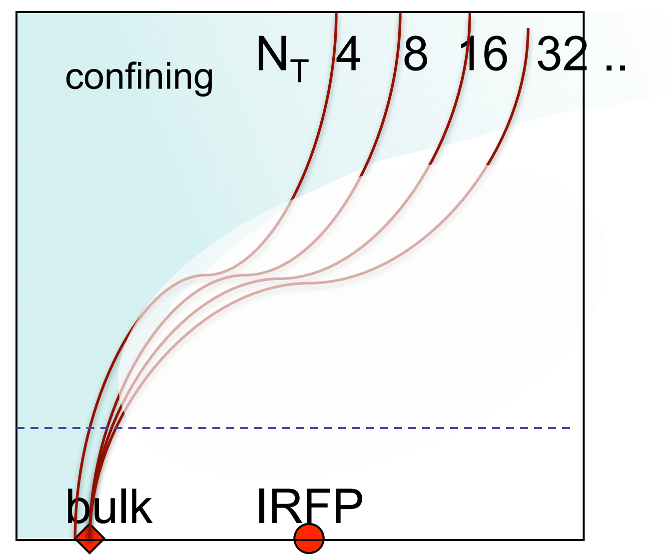
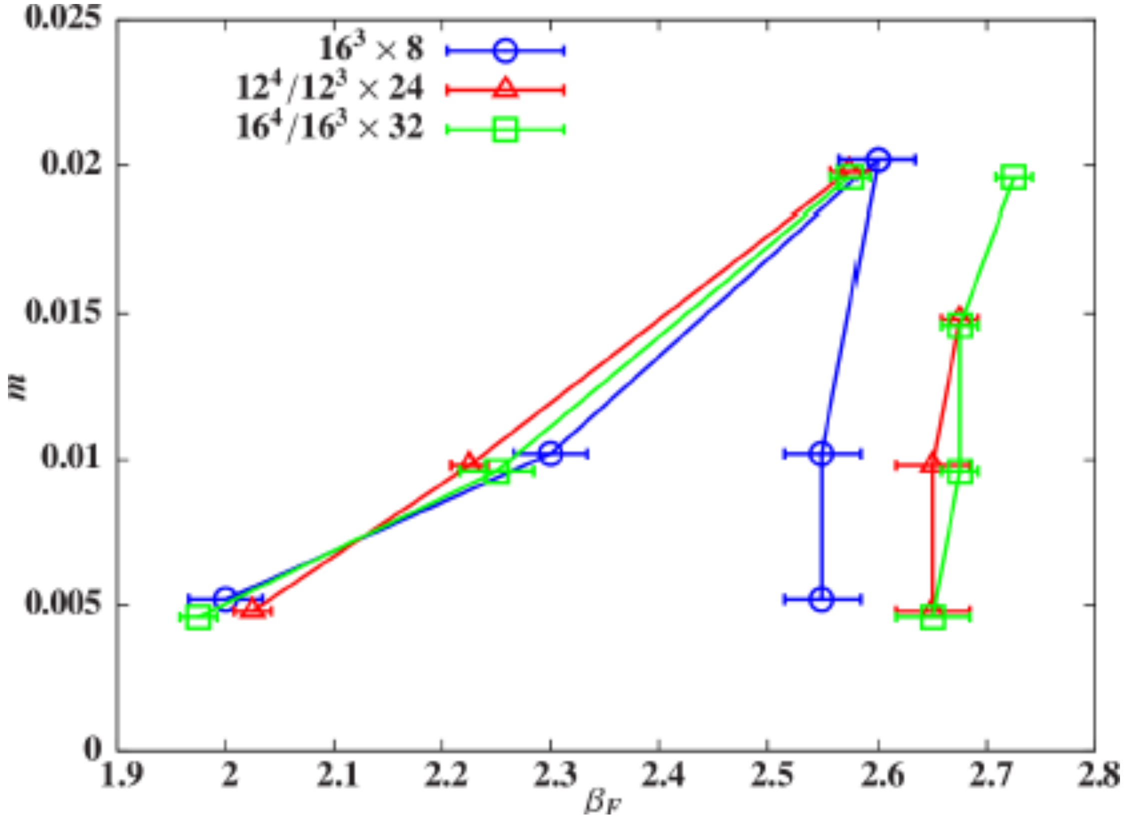




$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

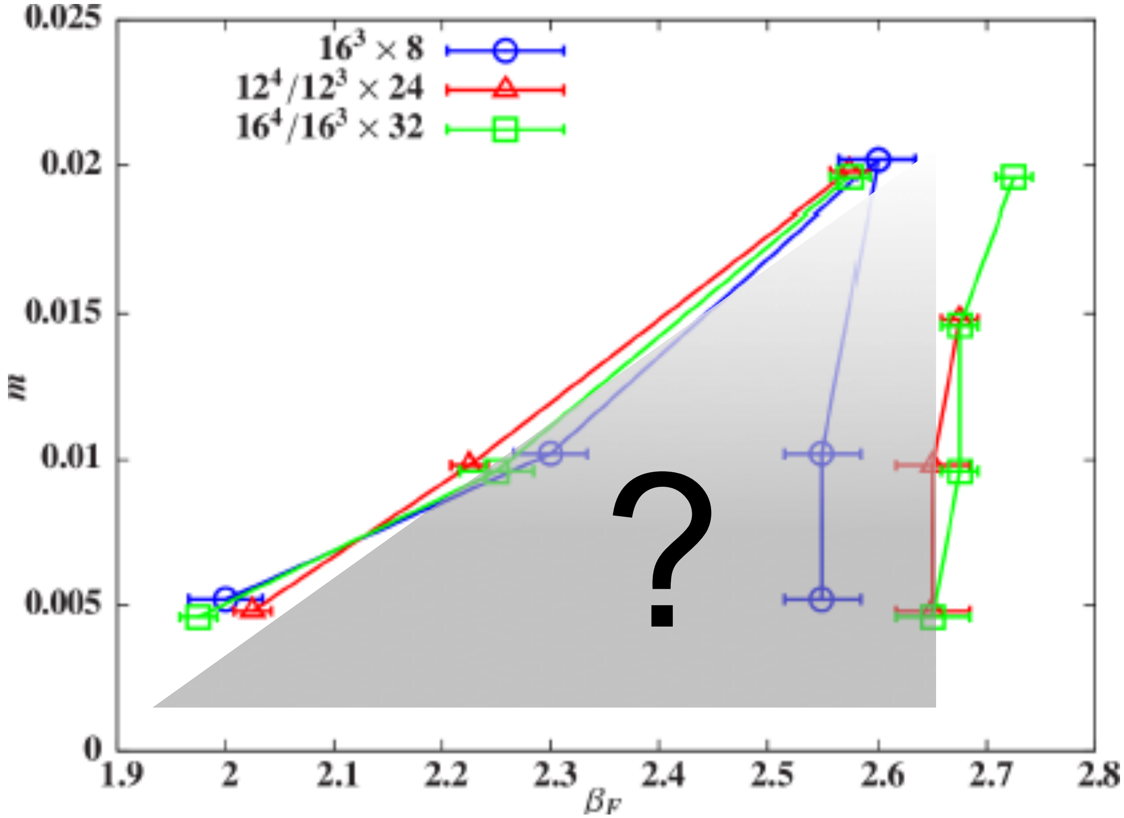
Similar transitions were observed previously by INFN/Groeningen group and LHC collaboration

Phase diagram β-m plane N_f=12



Intermediate phase bordered by bulk 1st order transitions

Phase diagram β-m plane N_f=12



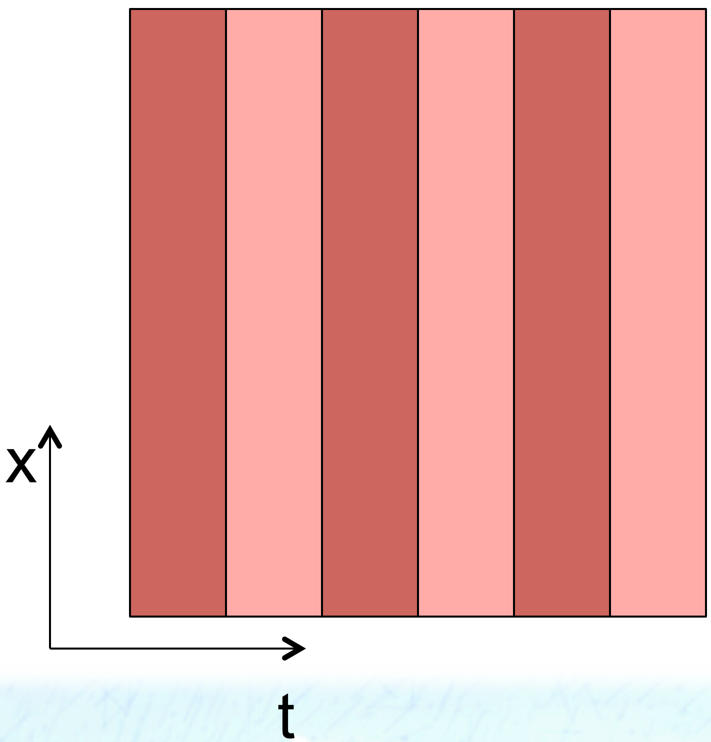
Intermediate phase bordered by bulk 1^{st} order transitions

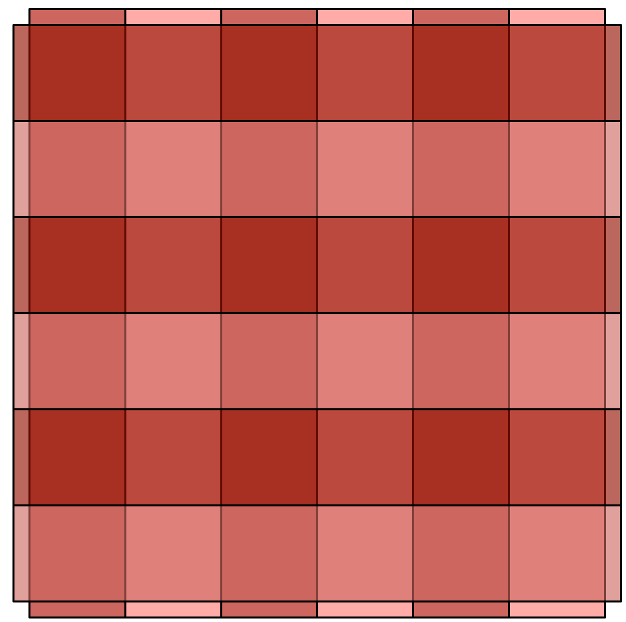
New symmetry breaking pattern in the IM phase

Single-site shift symmetry (S^4) of the staggered action

$$\chi(n) \to \xi_\mu(n)\chi(n+\mu), \qquad \xi_\mu(n) = (-1)^{\sum_{\nu>\mu} n_\nu}$$
$$U_\mu(n) \to U_\mu(n+\mu),$$

is broken → plaquette expectation value is "striped"



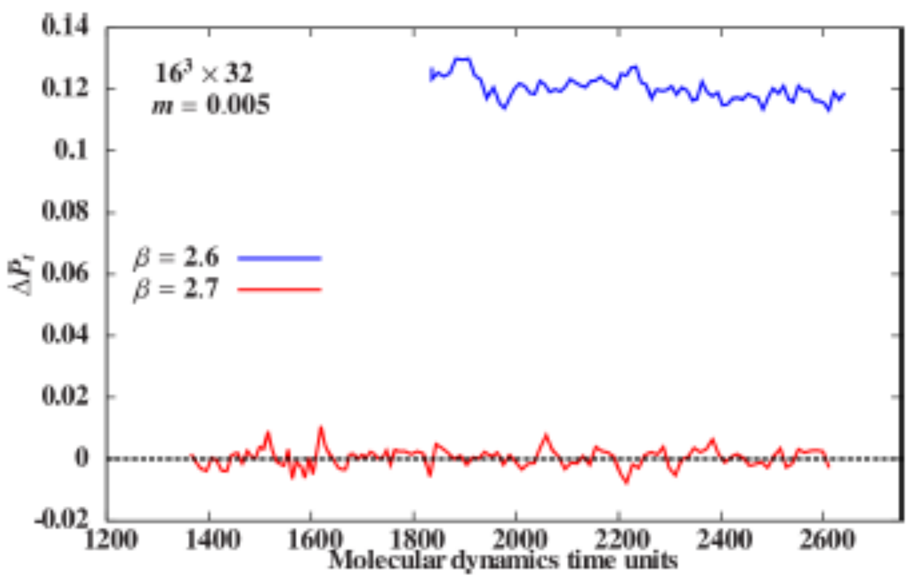


New symmetry breaking pattern

Order parameter I:

$$\Delta P_\mu = \langle \mathrm{Re\,Tr}\,\Box_n - \mathrm{Re\,Tr}\,\Box_{n+\mu} \rangle_{n_\mu \mathrm{even}}$$

Plaquette on even & odd time slices are different – this is on the background gauge configuration!



β = 2.6 IM phase

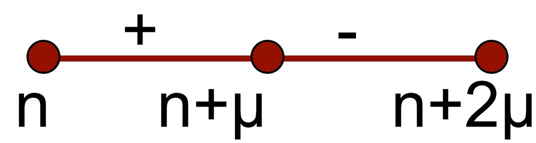
β=2.7 weak coupling phase

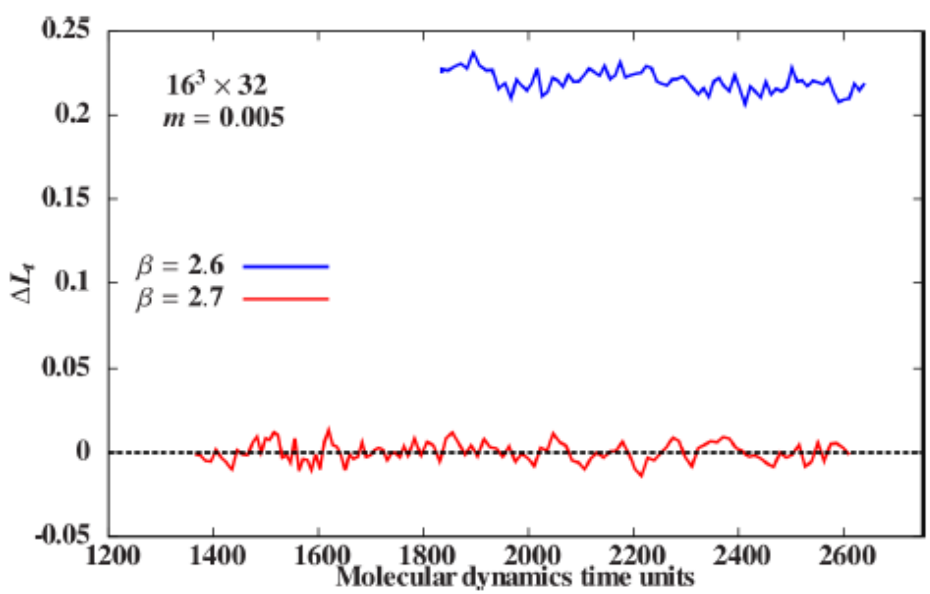
New symmetry breaking pattern

S^4 breaking occurs at the fermionic level:

Order parameter –II: link difference

$$\Delta L_\mu = \langle \alpha_\mu(n)\overline{\chi}(n)U_\mu(n)\chi(n+\mu) - \alpha_\mu(n+\mu)\overline{\chi}(n+\mu)U_\mu(n+\mu)\chi(n+2\mu)\rangle_{n_\mu \mathrm{ev}}$$





β=2.6 IM phase

β=2.7 weak phase

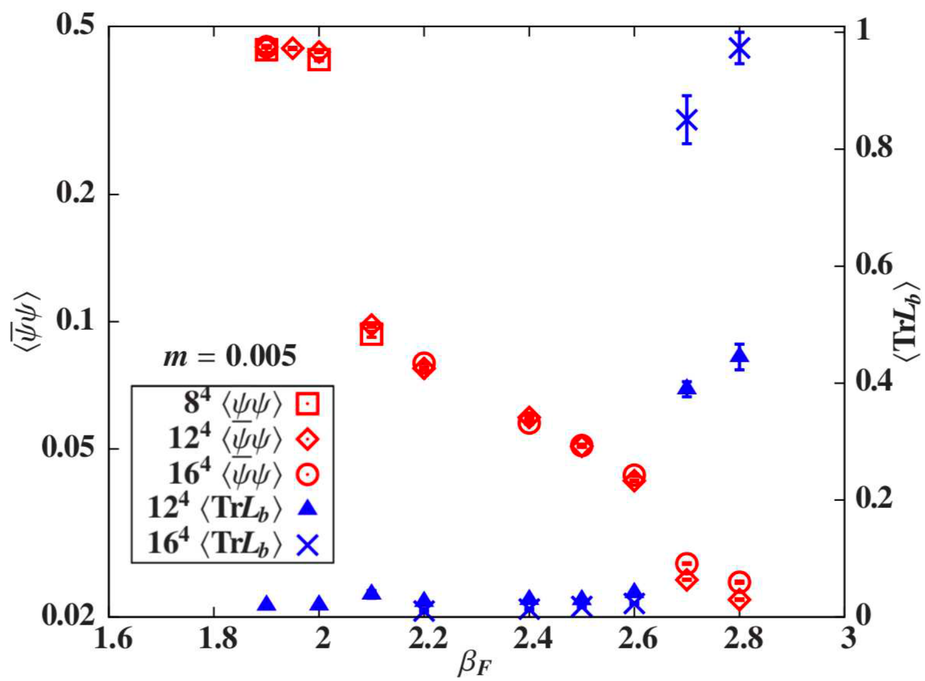
New symmetry breaking pattern

- Single-site shift symmetry is exact in the action.
- Both ΔP and ΔL are order parameters of S^4
- When S^4 is broken, the phase has to be separated by a “real” phase transition
- The S^4 broken ($\cancel{S}^4$) phase cannot go away with the volume
- S^4 is related to taste so this could be a special taste breaking

What are the physical properties of the S^4b phase?

The Polyakov line

Is it deconfining? Polyakov line is very noisy but the blocked Poly line is sensitive:



Blocked Poly line is measured on RG blocked lattices:

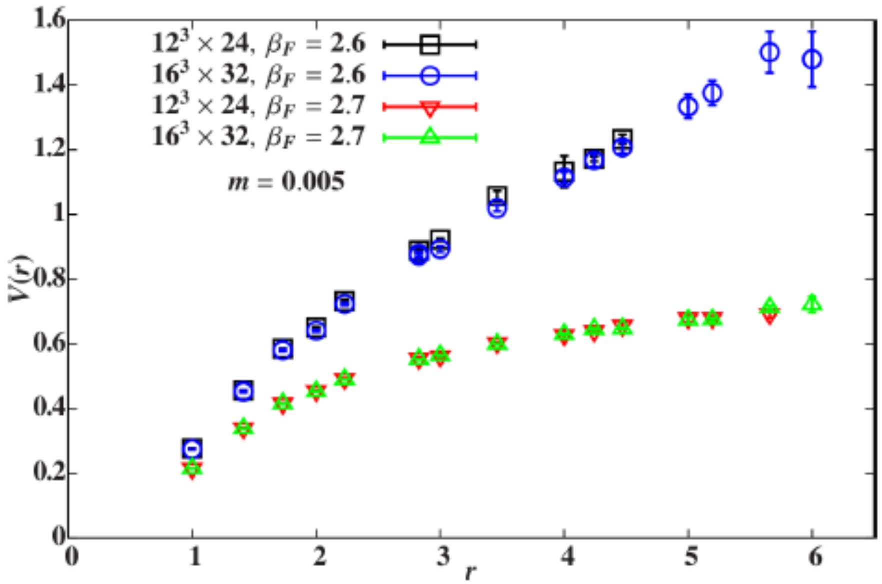
- improved Poly line

or

- Poly line on renormalized trajectory, after removing UV fluctuations

The static potential → Confinement!

Static potential on 12^3,16^3 volumes (no volume dependence!)
shows a linear term: r_0=2.1 – 2.7, $\sqrt{\sigma}$ =0.40 -- 0.48



β=2.6 – IM phase

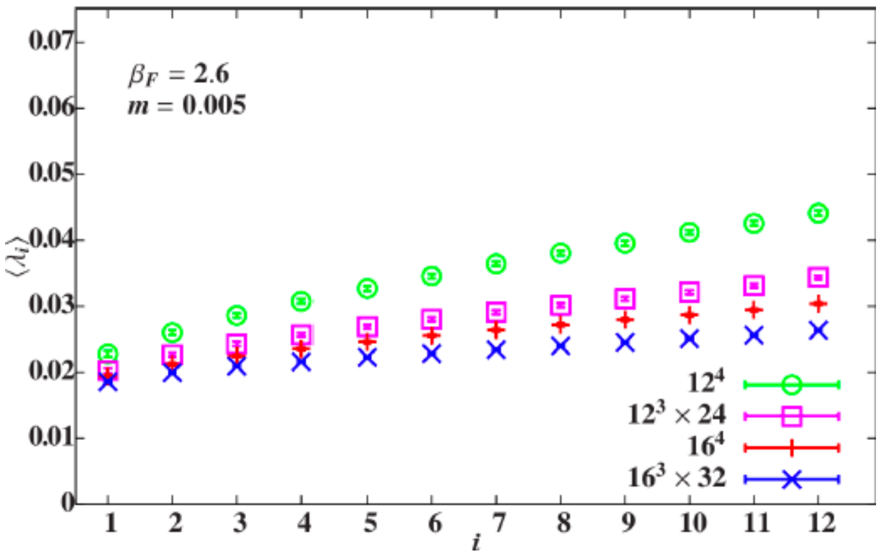
β=2.7 – weak coupling

No comment about the weak coupling side
from the potential – too small volume

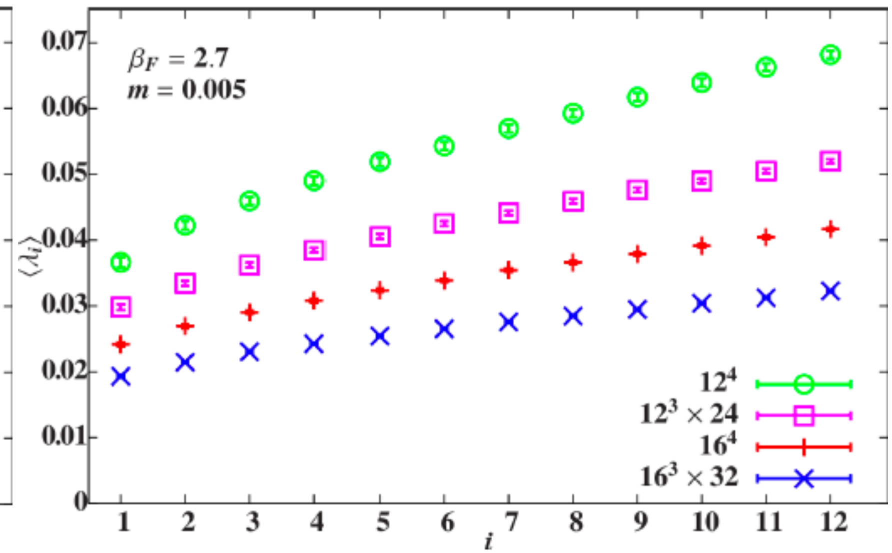
Chiral properties : Dirac eigenvalue spectrum

4 different volumes, 12 eigenvalues each:

β=2.6 – IM phase



β=2.7 – weak coupling phase



Qualitatively different – quantitative description?

Dirac eigenvalue spectrum

- RMT predictions require knowledge of the dynamics
- Simple volume scaling is more general. In the chiral limit

$$\rho(\lambda) \sim (\lambda - \lambda_0)^{\alpha}$$

λ_0 : soft edge

$$\int_m^n \rho(\lambda) d\lambda = \frac{n-m}{V} + O(1/V^2)$$

$$\lambda_n - \lambda_0 \sim \left(\frac{n - x_0}{V} \right)^{1/(\alpha+1)}, \qquad \frac{D}{\alpha+1} = y_m$$

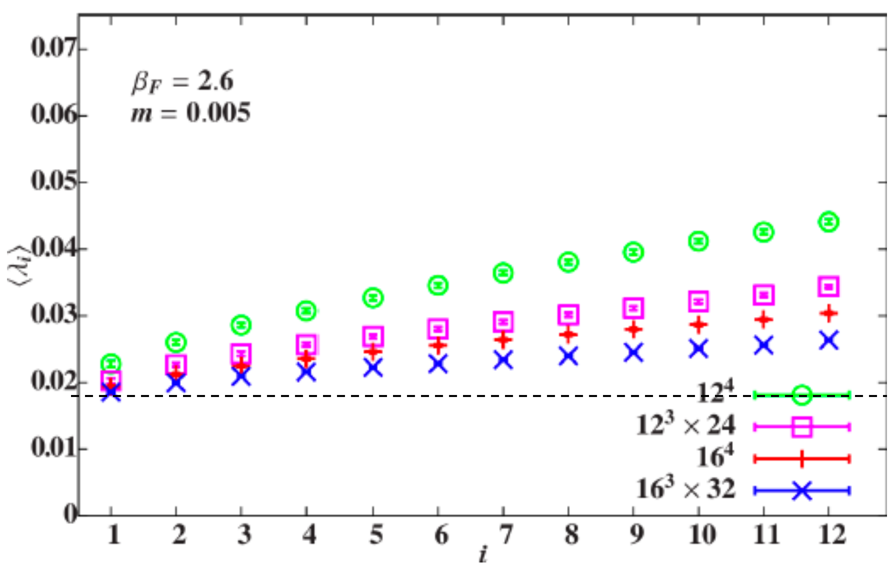
- Conformal IRFP : $y_m = 1 + \gamma^*$, : independent of V, β
- Confining system : $y_m = 1 + \gamma(L)$: in volumes smaller than the confinement scale

Dirac eigenvalue spectrum

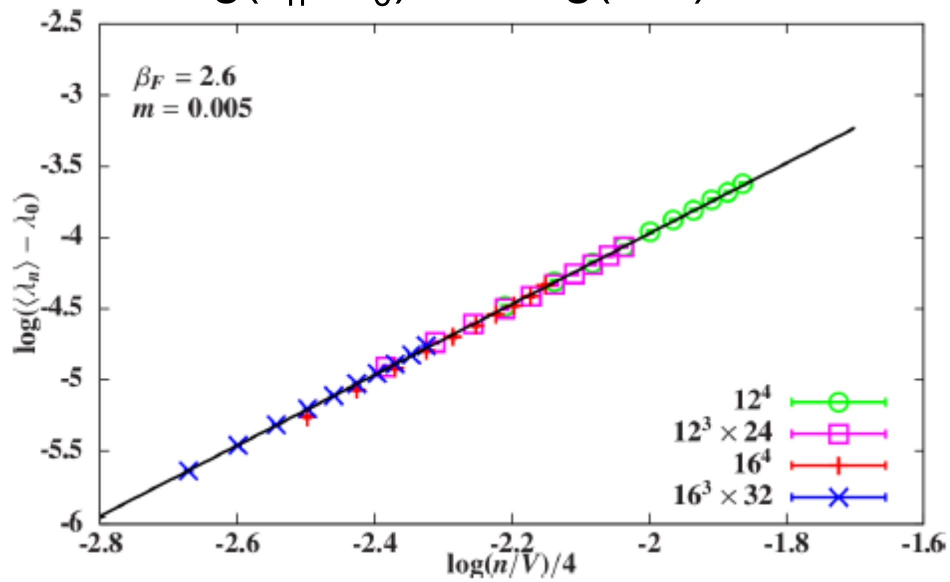
Fit in S^{4}b phase (β=2.6):

Needs soft edge λ_0=0.0175 with α=0.6(1) (RMT prediction: α=1/2)

Very chiral symmetric! (Even U(1)$_A$ restoring)

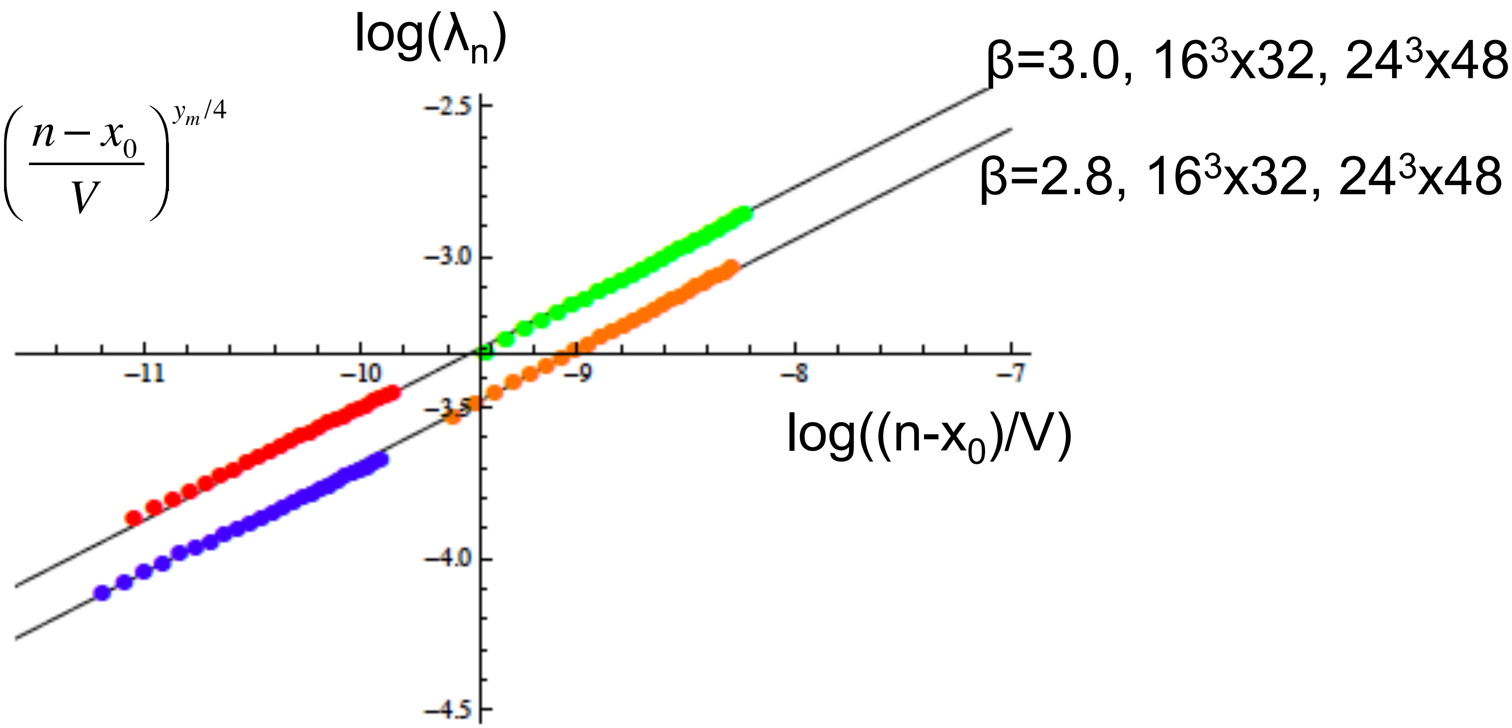


log(λ_n –λ_0) vs log(n/V)



Scaling of Dirac eigenmodes, $N_f = 12$, weak coupling side

$$\lambda_n \sim \left(\frac{n - x_0}{V} \right)^{\gamma_m/4}$$



Two coupling values, four volumes with 30 eigenmodes each are consistent, predict γ_m=0.47(2)

Very efficient method to determine the anomalous dimension

(we need larger volumes, other β, more eigenmodes to reduce error)

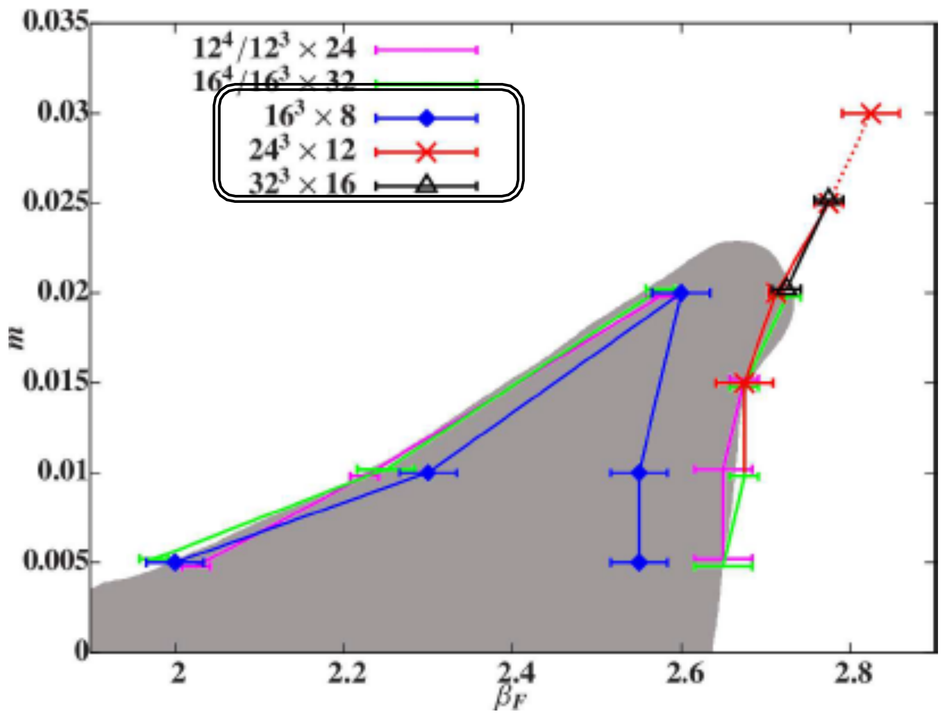
The S^4b phase

Is most likely a lattice artifact

- Breaks single-site translational symmetry
- It is confining with small correlation length
- It is chirally symmetric
- (yes, it would violate the ‘t Hooft anomaly matching in the continuum)

What happens at finite temperature?

Phase structure at finite T, N_f=12



N_T=12, 16 transitions

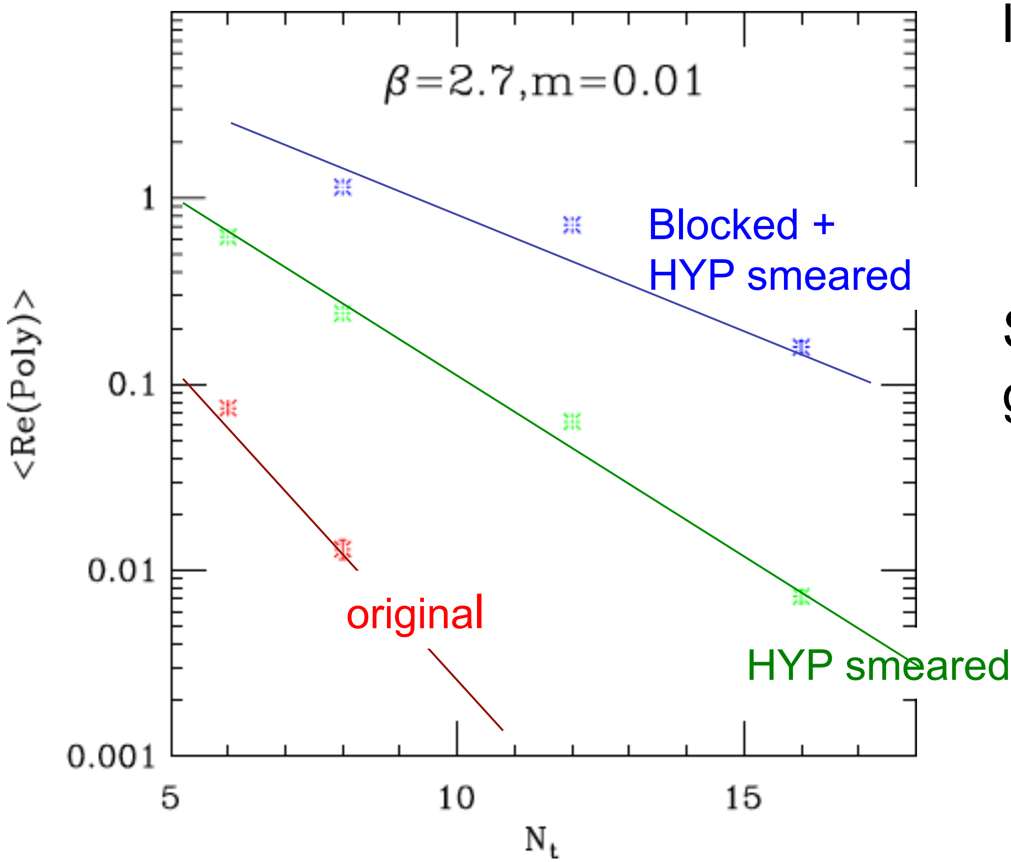
- indistinguishable
- run into the S^4b phase

The weak coupling, m<0.03 region is either

- conformal or
- has N_T >16

Preliminary; more data in progress

Improved Polyakov line



Poly line is difficult to measure at large N_t as it decays exponentially

$$\langle P \rangle \sim \exp(- f * N_t)$$

Smeared (HYP) or blocked Poly gives a better signal

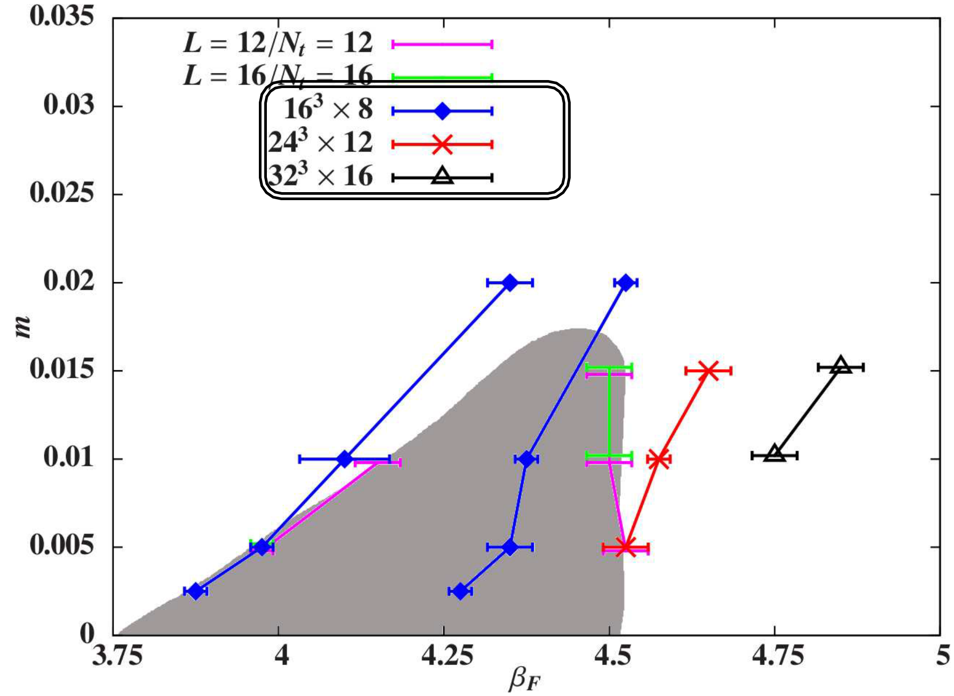
S^4b phase in other systems

There are signs of the intermediate phase with other $N_f=12$ actions

Is it unique to $N_f=12$?

No.

Phase structure with N_f=8



The S^4b phase, bordered by bulk transitions, is present
→ S^4b does not imply conformality

But N_T=12, 16 transitions behave differently: move toward $g^2 = 0$ as N_T increases

This is consistent with confinement

Preliminary; more data in progress

Summary & Outlook

These systems are complicated and have strange (strong coupling) lattice artifacts

Progress is steady but we need better understanding

The S^4b phase is present with 2 sets of staggered fermions. Could it show up in 2+1 flavor simulations?